

**FINAL REPORT**  
**DOE Project DE-FG07-99ID13770**  
**Figures 1 through 10 are proprietary information**

**Project Title:** Intelligent Automated Nuclear Fuel Pellet Inspection System (Phase II)  
**Report period:** May 24, 1999- July 31, 2002  
**Principal Investigator:** Shahla Keyvan, University of Missouri-Columbia

## **EXECUTIVE SUMMARY**

Quality control in fuel fabrication in the U.S. relies on human inspection of the manufactured fuel pellets before insertion into the zirconium fuel tubes. Generally, the pellets are examined for the following types of defects on their sides: 1) cracks, 2) chips, 3) unusual markings, i.e. water stain, and 4) machine banding. The ends of the pellets are checked for chip defect if edge misalignment is noticed on the pellet-pellet interface when viewing the pellets from the side.

At the present time, pellet inspection is performed by human operators using naked eyes for judgment and decision making on accepting or rejecting a pellet. Fuel pellet inspection is complicated due to the fact that some small degree of chipping or cracking is permissible. Unnecessary re-fabrication of pellets will be costly and too many low quality pellets in a fuel assembly is unacceptable. The current practice of pellet inspection by humans is tedious and subject to inconsistencies and error. In addition, manual inspection is cumbersome since inspectors must keep the pellet at arm's length and wear glasses to protect the lens of the eye. To improve the quality control in nuclear fuel fabrication plant an automated pellet inspection system is needed.

The main objective in this research work is to develop a computerized inspection system to automate the quality control process of nuclear fuel pellet with minimum human operator involvement. This would reduce radiation exposure to the workers, improve accuracy, and maximize productivity and uniformity of the inspection process. The system utilizes video images of the fuel pellets and provides a reliable inspection using artificial intelligence techniques.

Figures 1 through 10 show a sample screen shots of the user interface of the on-line inspection system developed in this project.

Two Ph.D. dissertations resulted from this project, one during Phase-I (**DE-FG07-98ID13644**) and one during Phase-II (**DE-FG07-99ID13770**). Two papers were published in Phase-I and one paper is published so far in Phase-II.

## OBJECTIVES AND ACCOMPLISHMENTS

The objective of the Phase-II of this project (**DE-FG07-99ID13770**) was to convert the off-line inspection system developed in Phase-I (**DE-FG07-98ID13644**) to an on-line system. The most recent version and updated off-line prototype system that uses original pellet images obtained in laboratory under controlled lighting condition was presented at the ANS conference in Milwaukee, Wisconsin in June 2001.

A good automated inspection system must go beyond good versus bad pellet identification. A good/bad pellet identifier in an inspection system would result in a high rejection rate of otherwise acceptable pellets and this is not acceptable economically. The approach in this project is to identify: 1) good versus bad pellet, 2) identify each defect, 3) incorporate the stipulated criteria for each identified defect, and 4) simulate the current manual inspection for pellet end inspection.

Two areas related to the design of the on-line system have been examined:

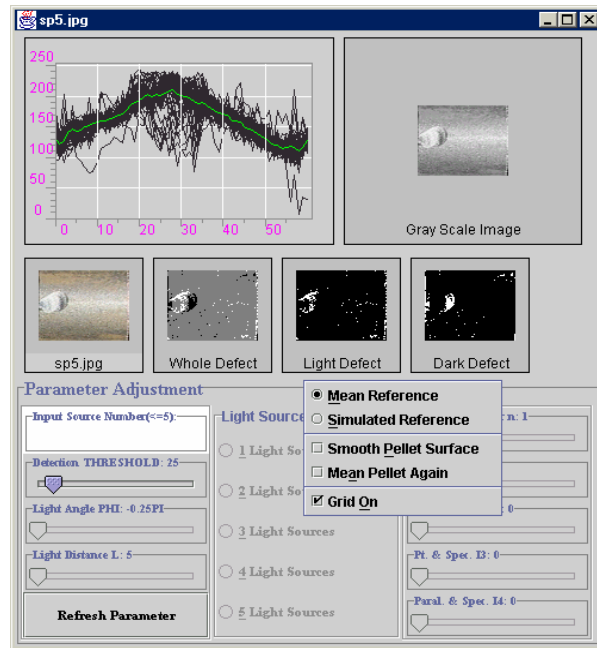
- a) Inspection criteria and their integration in the inspection algorithm. Two techniques, namely, Decision Tree (DT) and Fuzzy Logic, are incorporated for pellet defect recognition in the inspection algorithm.
- b) Conceptual design to integrate the automated inspection system with a system for arrival, inspection, and departure or exit process of the fuel pellets from the inspection area.

The first image acquisition from the manufacturing plant took place on Tuesday May 16, 2000, using two regular video cameras. The result of the image processing indicated the need for a progressive camera to accommodate the movement of pellets, which is the central part of the on-line conceptual design of Phase II. This progressive camera also provides the capability of capturing "STILL" images in addition to video images.

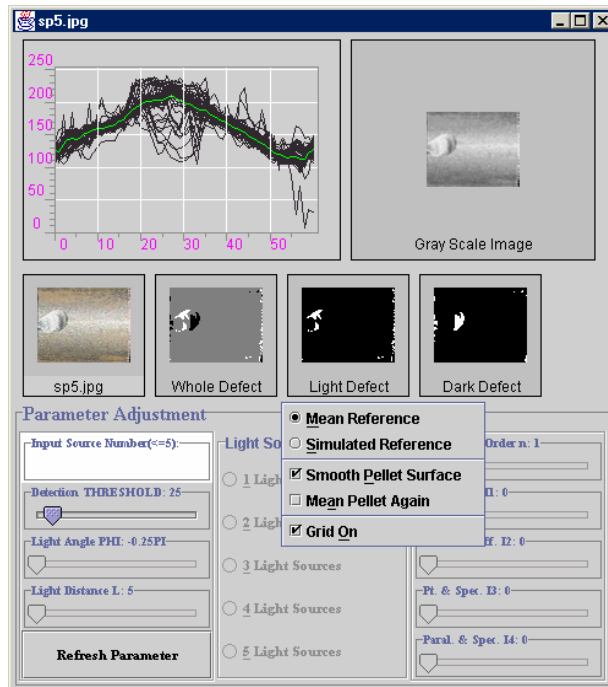
New images using a progressive camera were collected from the Westinghouse (formerly ABB) plant in Hematite Missouri on February 22, 2001. Two types of images were obtained: 1) video images, and 2) "STILL" images. For each category, images were collected using stationary pellets as well as moving pellets and both under various lighting conditions using portable flash light equipment compatible with the progressive camera.

The first attempt in evaluating and utilizing the new pellet images was to examine them using the off-line prototype system developed during phase I of this project. The result was compared with the original images that were obtained in the laboratory using regular camera under controlled lighting. The objective was to evaluate the performance of the "dynamic Reference" algorithm using the moving pellet images under various lighting conditions. The results show the excellent performance of the system in recognizing any type of abnormality. However, the algorithm needed to be upgraded in order to be robust with respect to light reflection, while identifying other flaws. This work began with simulation of many combinations of light sources and light reflections. The final results are described in the next section of this report.

Furthermore, a new algorithm was developed to smooth an image, therefore reducing noise. Figure 1 shows the impact of this noise removal algorithm on the pellet image in the box labeled “whole Defect”.



(a)



(b)

Figure1. Impact of smoothing on a pellet image, before (a), and after (b) noise removal

## SYSTEM DESCRIPTION

The on-line pellet inspection system developed in this research project consists of the following major components:

- 1) Two dynamic reference models “mean reference model” and “simulation reference model.” No prior database is used in either model. This is the uniqueness of this inspection system, where there is no need for a database as reference.
- 2) A Decision Tree (DT) algorithm and its associated features
- 3) A Fuzzy Logic algorithm and its associated features
- 4) Pellet size measurement algorithm

Currently the fuel pellet diameter is being measured by laser technique. Addition of this measurement to our inspection technique was a natural move as it could easily be incorporated into the already existing pellet image analysis algorithm of the system. This would increase the potential for commercialization of the system.

Furthermore, a Computer Aided Design “CAD” presentation is developed for the conceptual design of the arrival and departure of pellets as they move in front of the camera to be inspected. Major components of this design are: 1) pellets are moving while camera is stationary, 2) only one row of pellets moves in front of the camera, and 3) need only one camera.

Figure 2 shows the behavior of the “mean reference model” and the “simulation reference model” developed for the on-line inspection system. Both models are computationally efficient method.

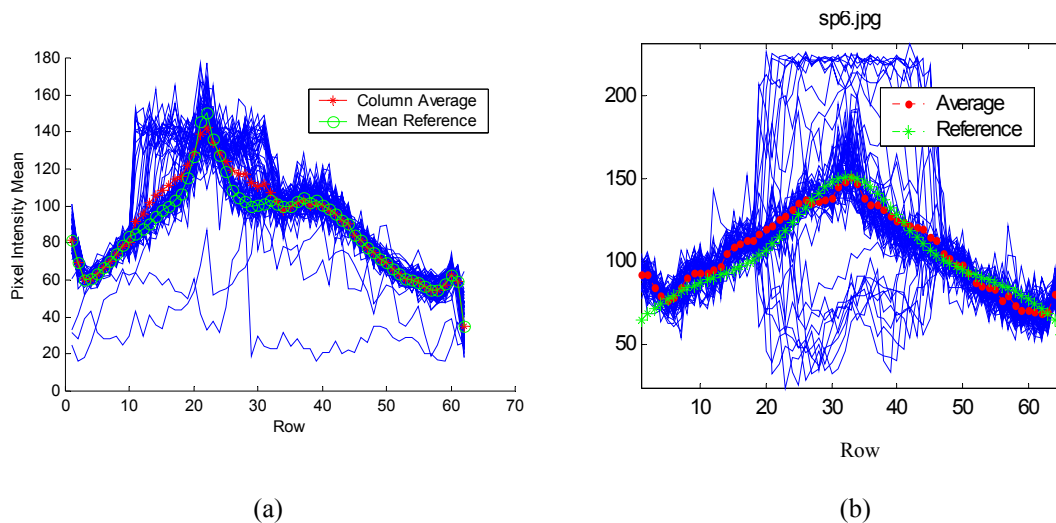


Figure 2. Comparison of pixel columns averages and the mean reference model (a) and Simulation reference model (b)

Figures 3 and 4 show the “simulation reference model” for two types of flaws, the banded and chip defects.

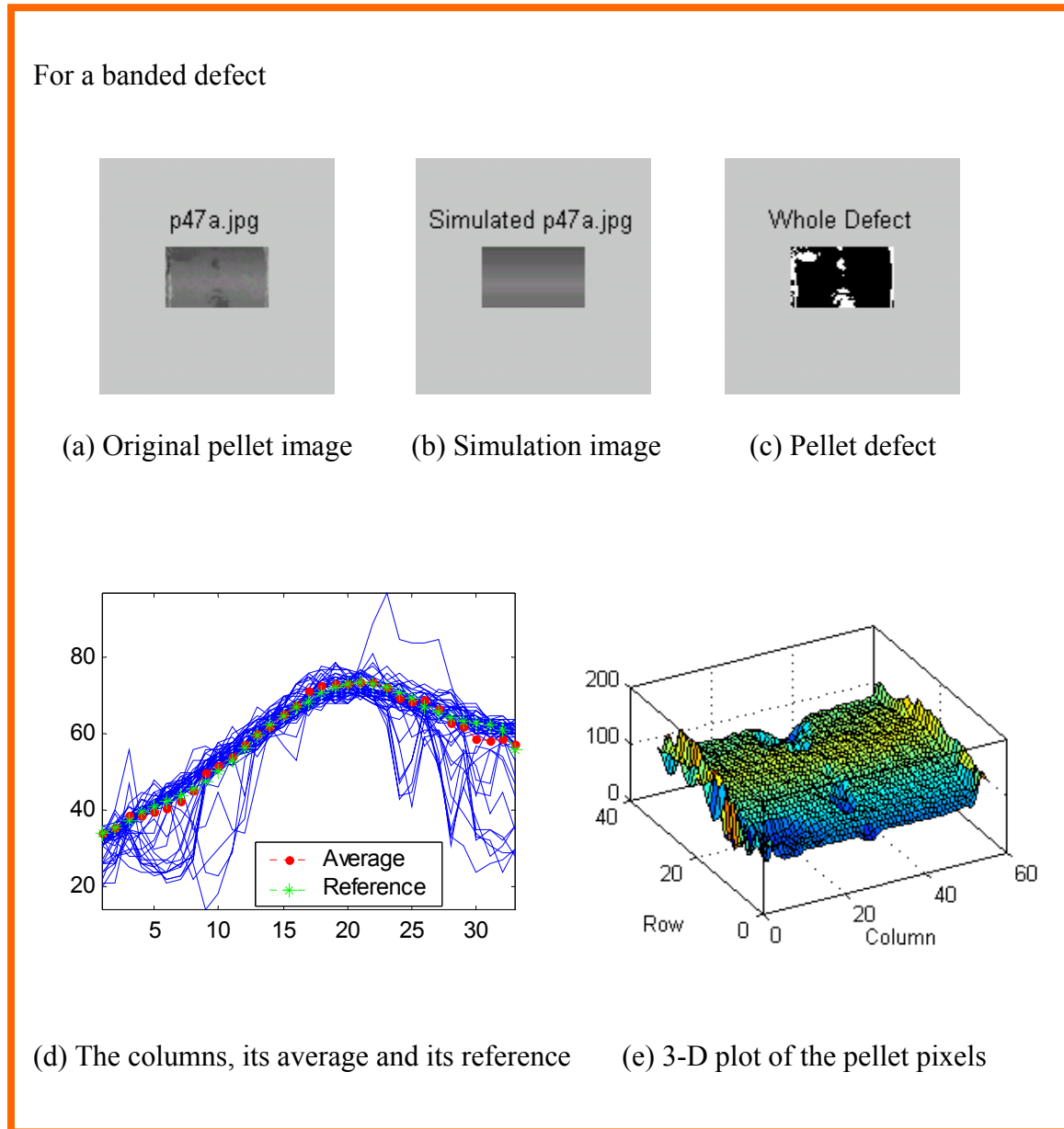
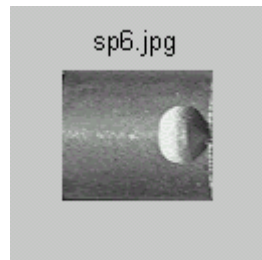
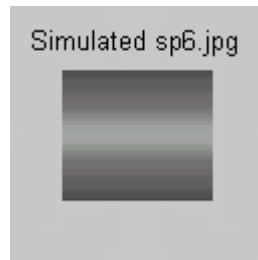


Figure 3. Simulation reference model for banded defect.

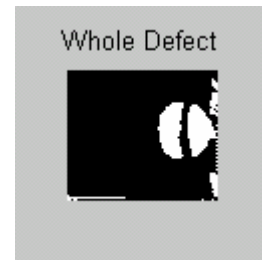
For a chipped defect



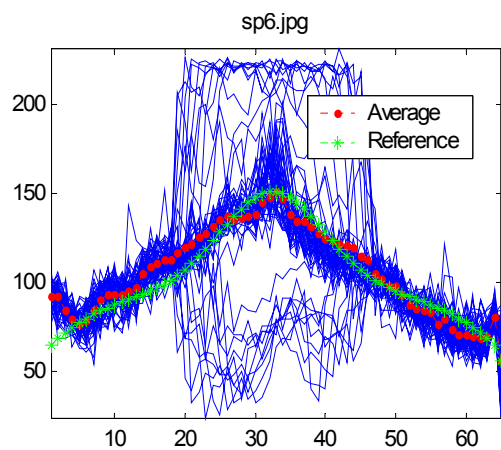
(a) Original pellet image



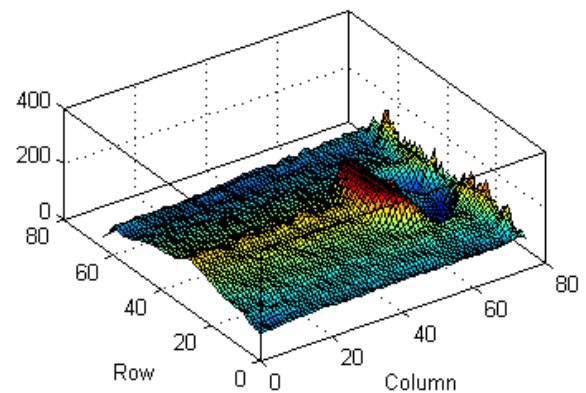
(b) Simulated image



(c) Pellet defect



(d) The columns, its average and reference



(e) 3-D plot of the pellet pixels

Figure 4. Simulation reference model for chip defect.

Figures 5 and 6 show the impact of the algorithm for noise removal using the simulated reference model. Figure 5 shows the result using the simulated reference without smoothing (noise removal). This figure shows the defect is detected correctly but with a lot of noise. Figure 6 shows the result using the simulated reference model with image smoothing. This figure shows the pellet defect is detected correctly with much less noise.

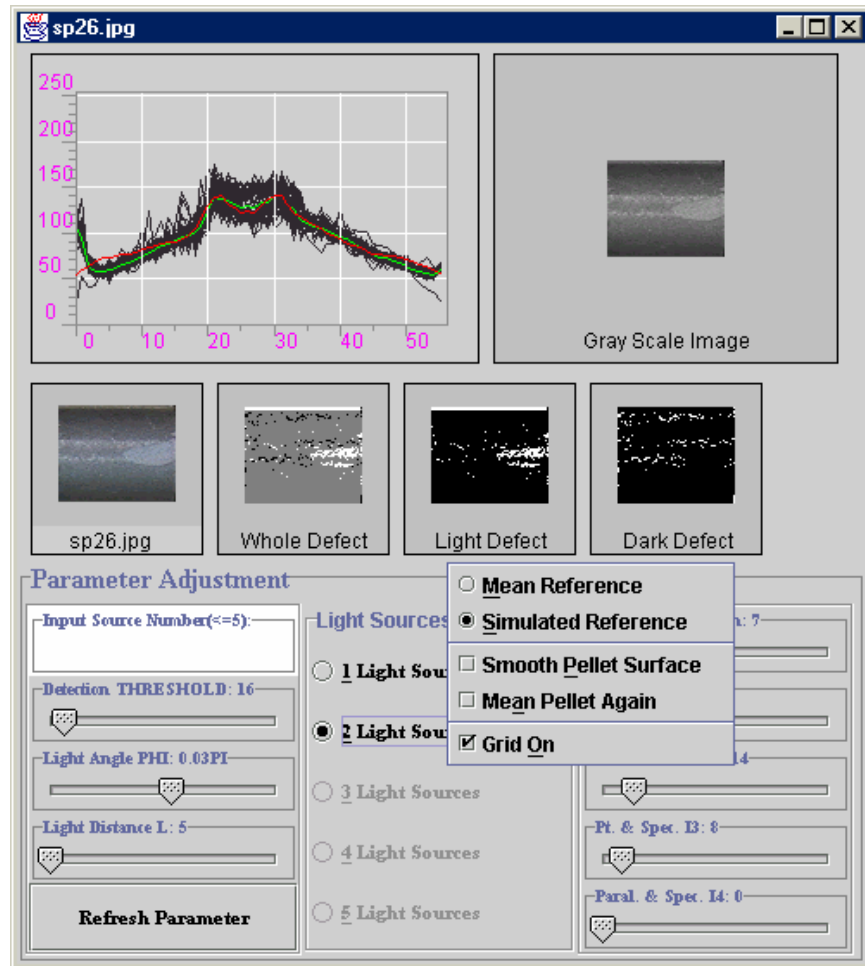


Figure 5. System performance without smoothing option

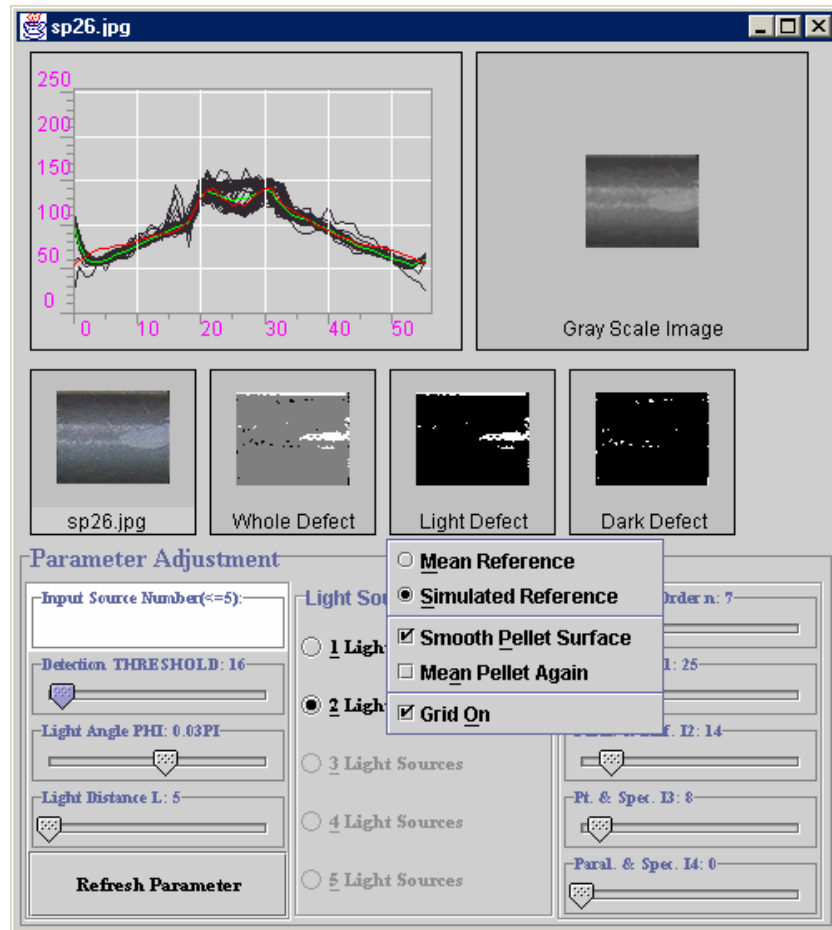


Figure 6. System performance with smoothing option

The pellet inspection system is developed using JAVA. Figure 7 shows the introduction frame of the inspection system.

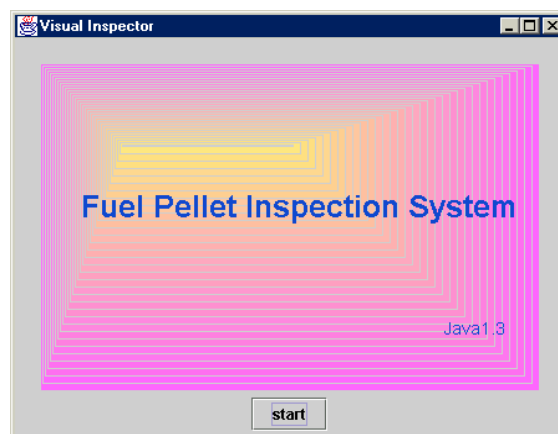


Figure 7. Introduction frame



Figure 8 shows the controller frame for the two major tasks of the inspection system, pellet size measurement and pellet defect inspection.

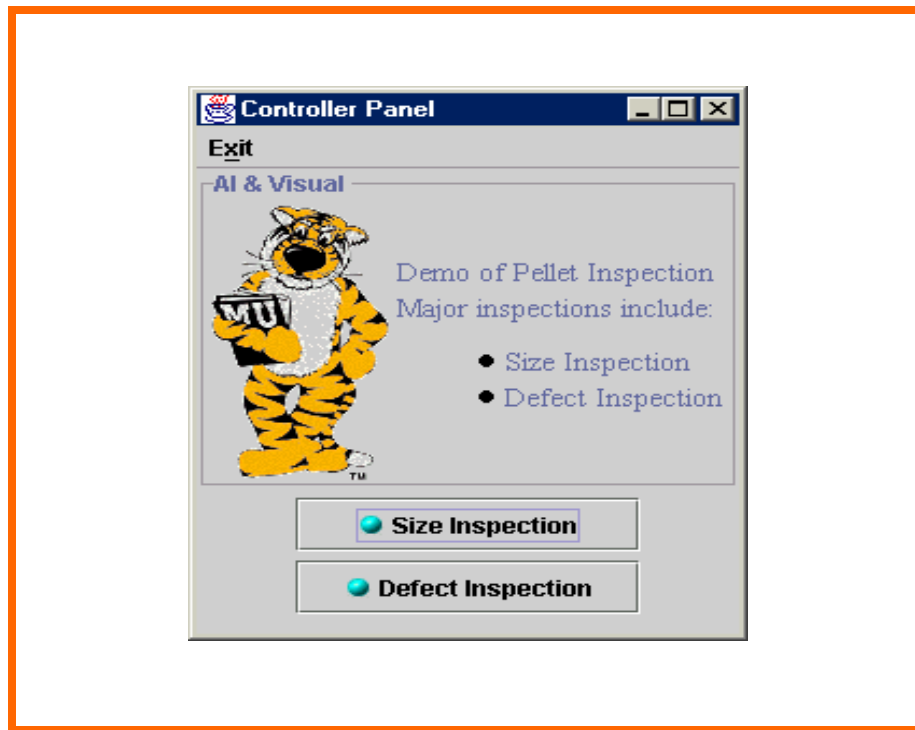


Figure 8. Controller panel of main tasks

Figure 9 shows the Graphical User Interface (GUI) of pellet size measurement. The top left image is the reference pellet image used as the "standard" for measurement. The result of measurements of the diameter and length (in inch) of each pellet by the inspection system are shown under the pellets.

Figure 10 shows the screen shot of the Graphical User Interface of the inspection system. The top right panel shows the data set of pellets to be inspected. One can browse the data set by clicking the forward (>>) or backward (<<) button. In the bottom panel one can choose the dynamic reference and set the appropriate parameter for it by clicking the button "Ref. Creation" which stand for reference creation. The option panel is to choose the algorithm for inspection. Panel "Info" shows the results of inspection. One can inspect one or all of the pellets in the data set by clicking "InspectOne" or "InspectAll" button respectively.

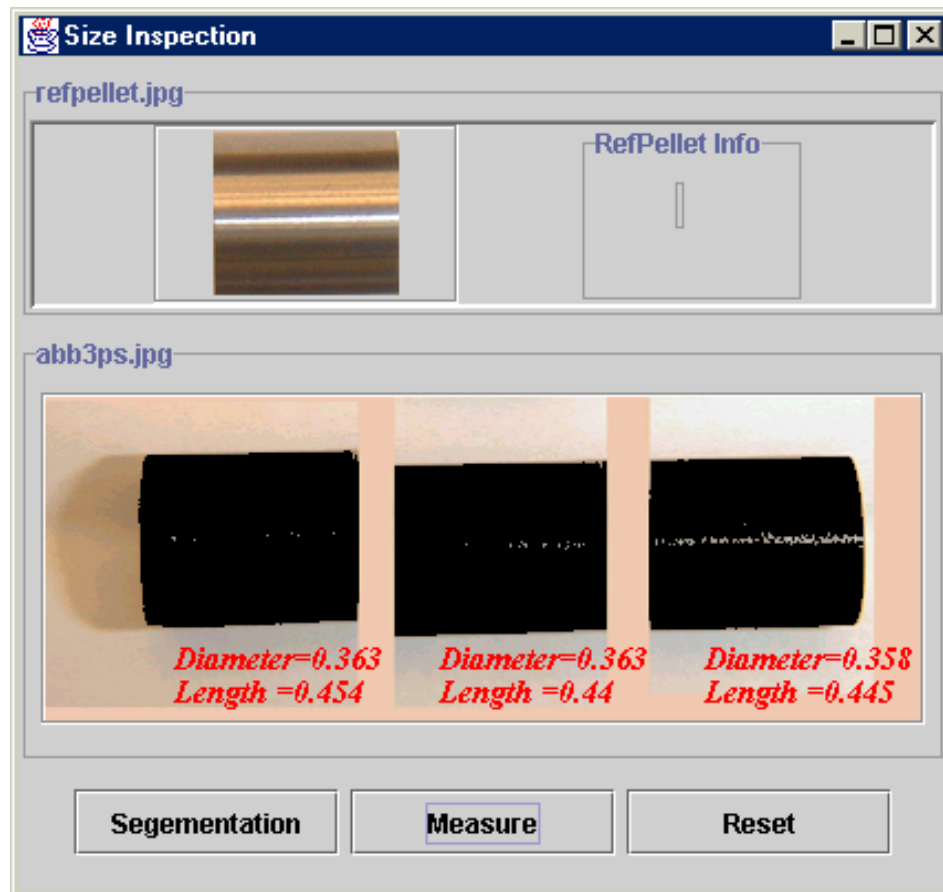


Figure 9. Results of the size measurement

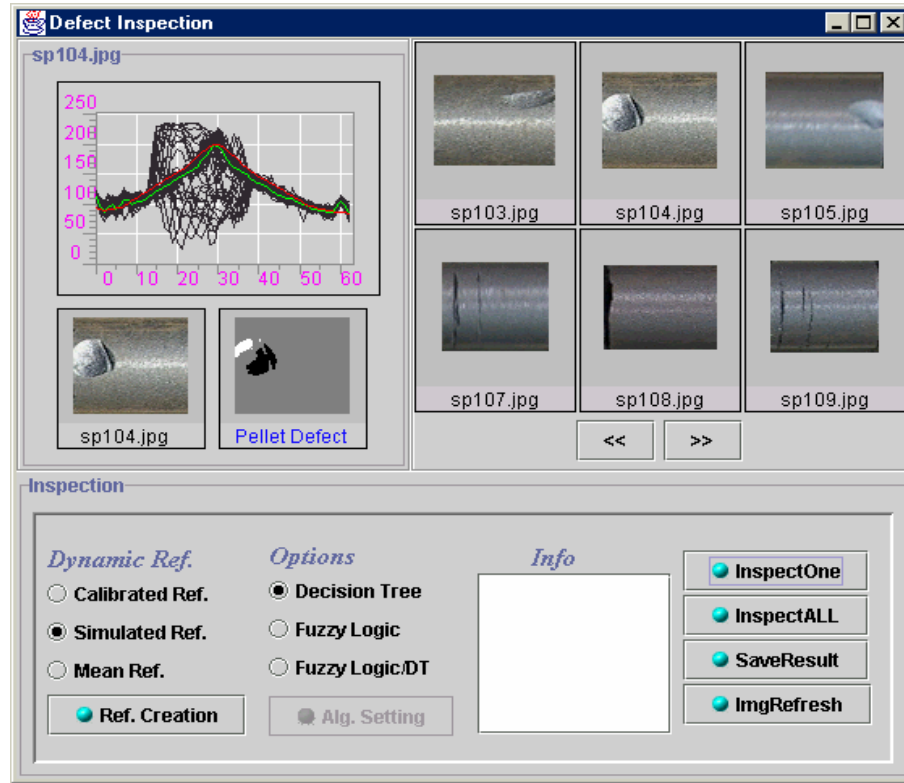


Figure 10. Graphical User Interface of the defect inspection system

Table 1 shows the classification matrix for inspection of 41 pellets (6 good, 17 chipped, 9 cracked, 9 end-missing) using simulated reference with the Decision Tree (DT) algorithm for classification. The accuracy of classification is 100%.

Table 1. Classification matrix of the DT classifier using simulated reference

Classified as	Good	Chipped	Crack	End-missing
Good	6	0	0	0
Chipped	0	17	0	0
Crack	0	0	9	0
End-missing	0	0	0	9

Using Dell personal computer with an 800Mhz Pentium processor, the average speed for inspection is 0.12 second per pellet. This means the system can inspect 8 pellets per second or 500 pellets in one minute.

Table 2 shows the classification matrix for inspection of the same 41 pellets using mean reference with the Decision Tree option for classification. The accuracy of classification is again 100%.

Table 2. The classification matrix of the DT classifier using mean reference

Classified as	Good	Chipped	Crack	End-missing
Good	6	0	0	0
Chipped	0	17	0	0
Crack	0	0	9	0
End-missing	0	0	0	9

Using Dell personal computer with an 800Mhz Pentium processor, the computing average speed for inspection is 0.101 second per pellet. This means the system can inspect 9 pellets per second or 594 pellets in one minute.

Similarly, the classification matrix for the fuzzy logic classifier using either mean reference or simulated reference model for inspection of the same 41 pellets is shown in Table 3.

Table 3. The classification matrix of the fuzzy logic classifier using either mean or simulation reference model

Classified as	Good	Chipped	Crack	End-missing
Good	6	0	0	0
Chipped	0	17	0	0
Crack	0	0	9	0
End-missing	0	0	0	9

Using Dell personal computer with an 800Mhz Pentium processor, the computing average speed for inspection is 0.081 second per pellet when using simulated reference. This means the system can inspect 12 pellets per second and 740 pellets in one minute. When using mean reference model the computing average speed for inspection is 0.074 second per pellet. This means the system can inspect 13 pellets per second and 810 pellets in one minute.

## CONCLUSIONS

The results show that using any one of the dynamic references (simulated reference or mean reference) and any one of the classifiers (DT or Fuzzy Logic) the accuracy of classification is 100% for all cases. Furthermore, the speed of the inspection is fast enough for on-line application of the inspection system.

Currently the fuel pellet diameter is being measured by laser technique. To make the inspection system more attractive for commercialization, a capability for pellet size measurement was added to the system at no additional cost to DOE. Furthermore, in addition to the required deliverable technique, namely, "Decision Tree" another technique "Fuzzy Logic" was also developed for the on-line inspection system at no additional cost to DOE. This project is successfully completed and ready for commercialization.